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Review Article

A Review of Flood Research: Trends, Methods, and Solutions

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Abstract: Urban flooding has emerged as one of the most pressing challenges of the 21st century, intensified by climate change, extreme rainfall, and rapid urbanization. Over the past two decades, research on this issue has expanded considerably in both scale and scope, producing significant advances while also revealing persistent gaps. This review synthesizes and categorizes studies published between 2000 and 2023, with the aim of identifying key research trends, achievements, limitations, and future priorities. Five dominant trajectories are highlighted: (i) the growing application of multidimensional and hybrid hydrological–hydraulic models, (ii) the expanded use of GIS, remote sensing, and satellite data for flood mapping, (iii) the rise of artificial intelligence, machine learning, IoT, and Big Data in forecasting and early warning, (iv) the integration of climate-adaptive urban planning with green–gray infrastructure, and (v) increased attention to policy frameworks, governance, and social equity. Despite these advances, challenges remain, including the shortage of high-resolution data in many developing countries, the limited transfer of numerical models into practice, and the lack of integration between science, urban planning, and community participation. Building on these findings, the review proposes four strategic directions for future research: developing flexible simulation models using open data, applying AI/Big Data/IoT more effectively in early warning and risk management, embedding nature-based solutions in urban design, and strengthening international cooperation and cross-border data sharing. The study concludes that advancing urban flood research requires interdisciplinary collaboration that bridges science, policy, and practice, thereby contributing to the development of smarter, more sustainable, and climate-resilient cities.

Keywords: Urban Flooding; Hydraulic Modeling; Remote Sensing; Artificial Intelligence; Climate-Resilient.

Highlights:

- Reviews two decades (2000–2023) of urban flood research with emphasis on governance, equity, and adaptation.
- Identifies persistent gaps in data, policy integration, and community participation across developing regions.
- Proposes future priorities including climate justice, nature-based solutions, and international cooperation for resilient cities.

1. Introduction

Flooding is one of the most severe and widespread natural hazards, causing enormous economic, social, and environmental losses. Over the past two decades, the frequency and intensity of flood events have increased rapidly due to the combined effects of climate change, rapid urbanization, and the degradation of land and water resource management (Dhiman et al., 2019; Evelpidou et al., 2023; Shu et al., 2023; Swain et al., 2020). In addition to direct material damages, floods disrupt livelihoods, threaten public health, and heighten the vulnerability of poor and marginalized groups living in high-risk areas (Charuka et al., 2023; Cho & Chang, 2017). Consequently, Flood Risk Management (FRM) has emerged as a key interdisciplinary research field, bridging natural sciences, technology, socio-economics, and public policy.

Recent studies on FRM indicate a shift from traditional approaches based on structural measures (such as dikes and reservoirs) to more integrated, adaptive, and ecosystem-based solutions. This transition reflects the recognition that purely structural interventions are insufficient to cope with more frequent and less predictable extreme events (Evelpidou et al., 2023; Swain et al., 2020). As a result, many studies have emphasized the importance of non-structural measures, including land-use planning, wetland restoration, green infrastructure, and strengthening community capacity (Nsenga Kumwimba et al., 2023).

GIS, remote sensing, and artificial intelligence–based forecasting models are increasingly applied, improving the accuracy of hazard mapping, early warning, and decision support (Evelpidou et al., 2023). Moreover, many studies now integrate socio-economic and demographic factors into risk analysis, highlighting that vulnerability depends not only on natural conditions but also on the adaptive capacity of social systems (Shu et al., 2023; X. Yang et al., 2023).

Nevertheless, important research gaps remain. Most studies have been conducted at local or national scales, while cross-national comparative analyses and global syntheses are still limited (Charuka et al., 2023). Furthermore, the connection between scientific research and policy practice remains weak, particularly in integrating scientific data into urban development planning and water resource management. As Shu et al. (2023) emphasize, incorporating climate change scenarios into population projections and urban spatial planning is still in its early stages, leaving many regions unprepared to cope with future flood risks (Shu et al., 2023). While earlier reviews have tended to focus on specific regions, instruments, or policy instruments (e.g., Cho & Chang, 2017; Ding et al., 2022), this paper differs by systematically organizing recent urban flood research into five methodological and thematic domains and by explicitly linking technical advances with governance, equity, and practical implementation gaps at a global scale.

Against this background, this study aims to: (1) synthesize recent scientific research on flooding, (2) categorize it into key themes including modeling and forecasting, risk assessment, structural and non-structural measures, socio-economic impacts, and policy frameworks, and (3) evaluate the progress, limitations, and emerging trends in the field. In doing so, the paper seeks to provide a comprehensive overview that may help guide more sustainable and adaptive flood risk management solutions in the context of global climate change.

2. Global Research Trends on Flooding

Recent scholarship shows that flood research has evolved into five major thematic groups, reflecting a shift from purely structural approaches to more interdisciplinary and techno–social integrations (Table 1).

Table 1. Five thematic groups in global flood research: focus, methods, and critical differences

Thematic Group	Core Focus	Typical Methods / Tools	Representative Contributions	Critical Differences

1. Simulation & Modeling	Physical processes of flooding; forecasting & inundation dynamics	Hydrological–hydraulic models (1D/2D/3D), coupled models, GIS-based modeling	Improved forecasting accuracy; integration of physically based & data-driven models	Emphasizes *physical mechanisms*; requires high-quality data & computational resources
2. Risk Management & Policy	Governance frameworks, institutional capacity, climate adaptation policies	MCDA, policy analysis, institutional mapping, socio-political assessment	Highlights research–policy gaps; addresses governance, gender, social equity	Focuses on *institutional and regulatory dimensions*, not on physical modeling
3. Urban Planning & Design	Flood-resilient spatial planning; nature-based and green–gray infrastructure	SUDS, sponge-city planning, ecological design, land-use modeling	Demonstrates benefits of GI/NbS; links urban form with flood mitigation	Integrates *built environment* and *ecological approaches* rather than technology-only solutions
4. Early Warning & Technologies	Real-time monitoring, hazard detection, predictive systems	IoT sensor networks, AI/ML forecasting, remote-sensing–supported alerts	Enhances accuracy and lead time; operational applications in emergencies	Strongly *technology-driven*, focusing on real-time operations and automation
5. Climate Change Impacts	Long-term exposure, sea-level rise, extreme rainfall trends	Climate models, scenario analysis, large-scale datasets & projections	Reveals global hotspots; quantifies climate-driven flood intensification	Centers on *long-term systemic drivers*, rather than immediate risk management

The first group consists of studies on flood simulation and modeling, which play a foundational role in forecasting and risk assessment. Research employing remote sensing, GIS, and hydro-meteorological models has led to significant improvements in both short-term and long-term forecasting (Monika et al., 2025). Recent work has also begun to couple physically based models with data-driven techniques, although most AI-oriented developments are discussed more explicitly in the fourth thematic group on early warning and supporting technologies (Akhavan et al., 2025) (Akhavan et al., 2025).

The second group focuses on risk management and policy, where scholars emphasize the need to establish legal frameworks and multi-level governance to better adapt to climate change. Shu et al. (2023) highlighted the considerable gap between academic research and policy implementation, particularly in developing countries where the integration of climate scenarios into development planning remains limited (Shu et al., 2023). Likewise, Kovaleva et al. (2023) underscored the role of social and gender factors in disaster risk management, opening avenues for research on climate justice–oriented governance (Kovaleva et al., 2023).

The third group involves flood-resilient urban planning and design, characterized by concepts such as "sponge cities" and "green infrastructure," which enhance infiltration and water retention in urban spaces. For instance, Song (2019) demonstrated that integrating green infrastructure into planning can significantly reduce surface runoff and flood risk, while Nsenga Kumwimba et al. (2023) confirmed the role of ecological technologies in pollution control and in strengthening urban systems against extreme rainfall (Nsenga Kumwimba et al., 2023; Song et al., 2019).

The fourth group centers on early warning systems and supporting technologies, regarded as critical advances in mitigating damages. Recent studies integrating sensor networks, IoT, and artificial intelligence have proven effective in improving both accuracy and speed of warnings (Muhammad et al., 2023). Dang et al. (2025) emphasized that deploying intelligent warning systems can substantially reduce casualties in countries with weak infrastructure (Dang et al., 2025).

The final group addresses the impacts of climate change, with extensive evidence showing that sea-level rise, shifts in extreme rainfall patterns, and increasing storm frequency are key drivers of flood risk in the 21st century. Evelpidou et al. (2023) demonstrated that coastal regions in the Mediterranean and South Asia face increasing exposure, while Kovaleva et al. (2023), in a global study, stressed that incorporating climate scenarios into risk management is one of the most urgent priorities (Evelpidou et al., 2023; Kovaleva et al., 2023).

Taken together, these five groups illustrate a clear trend: flood science is steadily moving away from purely technical interventions toward multidimensional approaches that combine advanced technologies with socio-economic and policy factors (see Figure 1). While modeling and forecasting provide the scientific foundation, policy and planning studies shape the pathways for practical application. At the same time, early warning systems and new technologies form a bridge between science and communities, while climate change research offers a long-term perspective for sustainable development. This trajectory highlights that global flood research is increasingly interdisciplinary, integrative, and closely tied to the pursuit of climate justice.

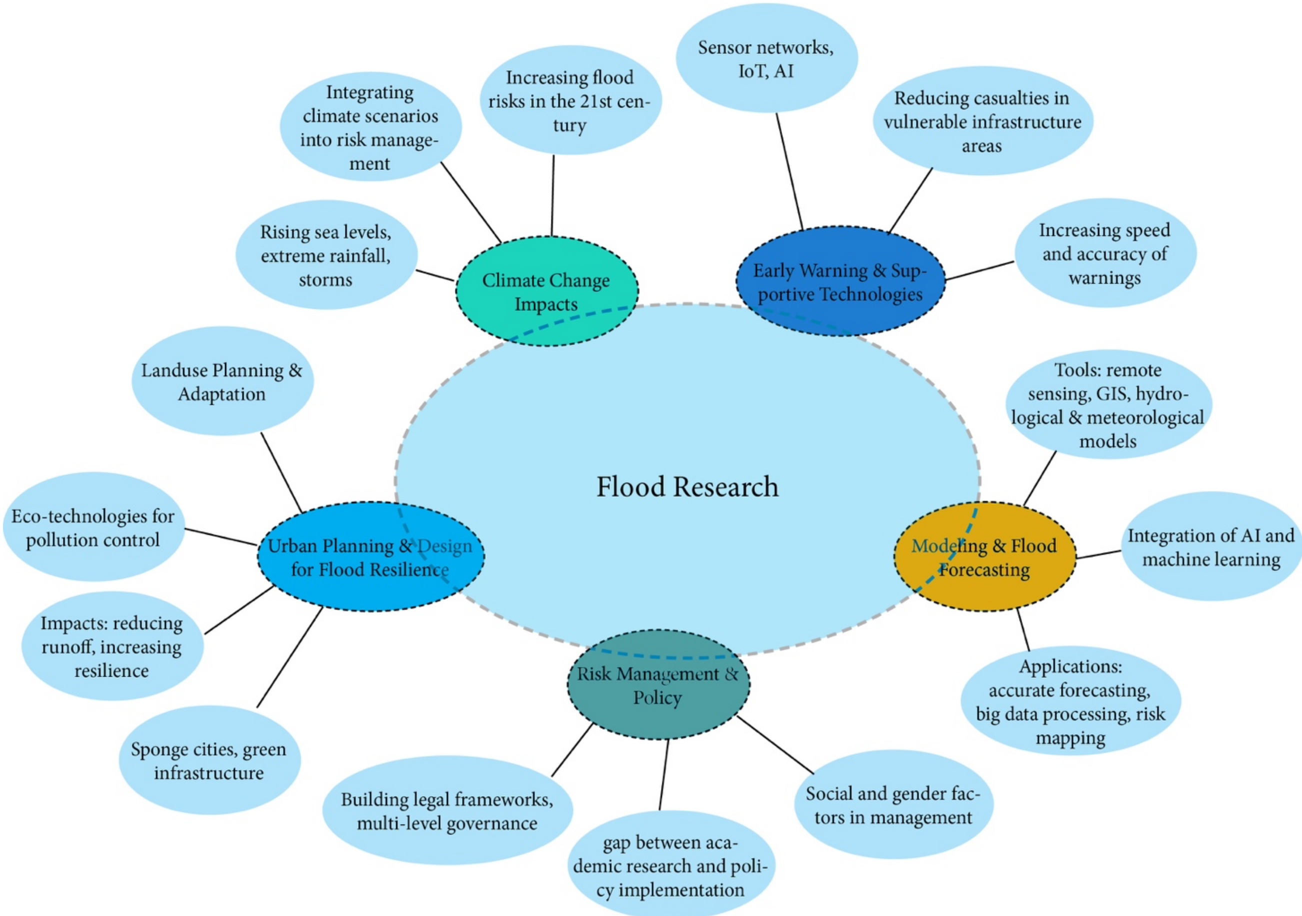

Figure 1. Diagram of the five main pillars contributing to flood research studies

3. Research Methods

This study applies a systematic narrative review combined with qualitative and bibliometric analysis to identify research trends, thematic clusters, and knowledge gaps in urban flood studies during 2000–2023, following established guidelines for high-quality literature reviews (Snyder, 2019). For the bibliometric component, the bibliographic mapping software VOSviewer was employed to visualize keyword co-occurrence and co-citation networks (Donthu et al., 2021).

Data were retrieved from three major databases: Web of Science, Scopus, and Google Scholar, ensuring coverage and cross-platform comparability (Martín-Martín et al., 2018). The search strategy was organized into three groups of keywords: (i) management ("urban flood risk management," "flood resilience," "climate change adaptation AND flooding"); (ii) modeling and data ("hydrological/hydraulic modelling AND urban flood," "1D–2D coupled model," "remote sensing AND flood mapping"); and (iii) technology and warning ("IoT flood early warning," "machine learning/deep learning AND flood prediction"). Queries were optimized with Boolean operators and adjusted according to the specifications of each database (Donthu et al., 2021).

Selection criteria included peer-reviewed publications (reviews and original research), full-text in English, published between 2000 and 2023. Grey literature, out-of-scope works, and duplicates were excluded. Approximately 2,500 initial records were screened down to 720 and ultimately 320. Data were extracted using a standardized form (geographical context, data type, methodology, theme, and evaluation indicators) and content was coded into five thematic clusters (Van Eck & Waltman, 2010). A PRISMA-style summary of the study identification, screening, and inclusion process is presented in Table 2.

Table 2. Prisma-style summary of study identification, screening, and inclusion

Stage of Review Process	Description	Number of Records
Identification	Records retrieved from Web of Science, Scopus, and Google Scholar	**2,500**
	Duplicates removed	**– 620**
Screening	Titles and abstracts screened	**1,880**
	Records excluded (irrelevant, non-English, grey literature)	**– 1,160**
Eligibility	Full-text articles assessed for eligibility	**720**
	Full texts excluded (out of scope, insufficient methodological detail)	**– 400**
Included	Final studies included in qualitative synthesis and thematic coding	**320**

4. Results

4.1. Global Methodological Landscape of Contemporary Flood Research

Drawing on a synthesis of more than 320 peer-reviewed studies published between 2000 and 2023, contemporary flood research can be grouped into five major methodological domains.

The largest body of work, representing approximately 35 to 40 percent of the literature, centers on hydrological and hydraulic modeling. This strand includes 1D, 2D, 3D, and coupled hydrodynamic models that support flood simulation, inundation mapping, and event reconstruction. Widely adopted tools such as HEC-RAS, MIKE 11/21/FLOOD, SWAT, LISFLOOD-FP, and TELEMAC dominate this field. As Singh et al. (2023) note, nearly 70 percent of hydraulic studies in Asia rely on hybrid 1D to 2D configurations. Despite their technical sophistication, these models remain constrained by the availability and quality of input data, particularly DEMs, rainfall series, and discharge observations in data-scarce regions.

A second major research stream, which accounts for roughly 20 to 25 percent of publications, employs GIS and remote sensing techniques to detect, monitor, and map flood dynamics. This body of work frequently utilizes satellite imagery, UAV-based data collection, and spatial analytic tools. According to Sadiq et al. (2023), Sentinel-1 and Landsat imagery together constitute more than 60 percent of global satellite-based flood-mapping applications. The strengths of this approach lie in its broad spatial coverage, rapid data acquisition, and relatively low cost, although limitations persist regarding spatial and temporal resolution as well as cloud contamination.

A third and rapidly expanding research area involves machine learning and artificial intelligence, which currently contribute approximately 15 to 18 percent of all flood-related publications. The growth of this field is notable, rising from only 5 percent in 2010 to nearly 17 percent by 2023. Studies increasingly apply ANN, SVM, Random Forest, LSTM, CNN, and hybrid deep-learning architectures for flood forecasting, susceptibility mapping, and risk prediction. Key challenges identified in this body of work include limited interpretability, sensitivity to training-data quality, and difficulties in operational deployment at scale.

The fourth methodological group, which represents about 12 to 15 percent of the literature, focuses on flood risk assessment, urban planning, and the role of green and blue infrastructure in mitigating impacts. This strand encompasses sustainable drainage systems, sponge-city initiatives, and a range of resilient urban design strategies. Evidence indicates substantial benefits. Manandhar et al. (2023) demonstrate the hydrological effectiveness of green–blue infrastructure, while Ding et al. (2022) highlight the potential of sponge-city pilot districts in China as real-world laboratories for nature-based solutions.

The final methodological domain consists of policy analysis, governance, and community resilience, which together account for approximately 10 to 12 percent of published studies. This group includes multi-criteria decision analysis, institutional assessment, and examinations of governance frameworks that shape flood-risk management. emphasizes persistent gaps between scientific modeling and local institutional capacity, and Raza (2023) stresses the importance of community-based approaches that strengthen participation in early-warning systems.

Taken together, these five domains constitute a complementary methodological ecosystem in contemporary flood research. Hydrological and hydraulic models provide the foundation for understanding physical flood processes, while GIS and remote sensing contribute essential spatial observations that support monitoring and mapping. Advances in artificial intelligence and machine learning enhance predictive capabilities and improve the accuracy of flood forecasting. Urban planning and green–blue infrastructure research introduce design-oriented solutions aimed at mitigating impacts, and governance-oriented studies translate scientific insights into policy frameworks and community-based actions. The central challenge emerging from this synthesis is how to integrate these diverse methodological groups into coherent, multi-layered flood-management systems that can operate effectively across different spatial, institutional, and socio-ecological contexts.

4.2. Key Empirical Insights from the Five Dominant Research Domains

A review of previous studies across the five methodological domains reveals several consistent empirical patterns that inform contemporary flood analysis. Within the hydrological and hydraulic modeling literature, researchers widely agree that increasing urbanization and intensifying rainfall events amplify runoff generation, peak discharges, and inundation depths. O'Donnell and Thorne (2020) demonstrate that rising impervious surface cover can increase runoff by approximately 30 to 50 percent. Improvements in modeling techniques have also been documented, with hybrid 1D to 2D frameworks reducing inundation-mapping error by 20 to 35 percent (Gao et al., 2023). In Australia, climate-adjusted hydraulic models have further enhanced the reliability of design-flood estimates by about 15 percent (Wasko et al., 2023). These findings highlight both the sensitivity of hydrological processes to land-use change and the importance of refined model architectures in improving prediction accuracy.

Studies employing GIS and remote sensing similarly underscore the value of spatial observation in flood detection, monitoring, and vulnerability assessment. High-resolution synthetic aperture radar (SAR) imagery, for instance, consistently achieves classification accuracies of 80 to 90 percent in mapping flood extents (Sadiq et al., 2023). The integration of multiple sensors has also proven advantageous, with multisensor fusion techniques improving detection performance by 25 to 40 percent compared to single-sensor approaches. These advances demonstrate the growing capacity of spatial technologies to support rapid and reliable flood assessment, particularly in regions with limited ground-based monitoring.

The machine learning and artificial intelligence literature shows a marked improvement in forecasting skill and susceptibility analysis. Deep learning architectures such as ANN and LSTM reduce prediction errors, measured through RMSE and MAE, by approximately 10 to 45 percent (Yaseen, 2023). Hybrid models, for instance those combining convolutional neural networks with LSTM layers, enhance early-warning lead times by up to three hours (Li et al., 2023). Ensemble-based approaches such as Random Forest also achieve high classification accuracy, often in the range of 85 to 95 percent for flood-susceptibility mapping. These results collectively suggest that AI-driven approaches can outperform classical statistical techniques, although challenges remain regarding interpretability and data reliability.

Evidence from urban planning, green infrastructure, and climate-adaptation research highlights the effectiveness of nature-based and integrated design solutions. Green-infrastructure interventions have been shown to reduce peak flow by 20 to 30 percent while improving infiltration by 10 to 20 percent (Manandhar et al., 2023). Evaluations of China's sponge-city program indicate reductions in flood losses of 15 to 25 percent in pilot districts (Ding et al., 2022). Integrated watershed management approaches have also demonstrated substantial benefits, reducing damages during the 2013 extreme flood event by more than 30 percent (Qi et al., 2020). These findings illustrate how planning-oriented strategies complement engineering and technological approaches by targeting upstream drivers of flood risk.

Finally, governance, policy analysis, and community resilience studies emphasize institutional capacity, participatory engagement, and policy feasibility as decisive factors shaping flood-risk outcomes. Grigg (2023) reports that governance gaps can account for up to 40 percent of implementation delays in flood-mitigation strategies. Community-level innovations, including IoT-enabled early-warning systems, have improved evacuation readiness by 30 to 50 percent (Nabinejad and Schüttrumpf, 2023). In contexts where data availability is limited, integrated frameworks that combine climate projections, land-use scenarios, and remote-sensing inputs have proven especially beneficial, as shown in the findings of Trinh (2023). These studies collectively reaffirm that technical solutions must be embedded within strong institutional and social systems in order to achieve effective flood-risk reduction.

5. Discusssion

5.1. Conservation strategy Key Advances and Challenges

The literature reveals significant advances in technology, methodology, and governance frameworks; however, several major challenges persist because structural, institutional, and contextual barriers continue to limit the translation of scientific progress into practice.

First, regional and national disparities remain pronounced. Developed countries such as the United States, the United Kingdom, and Australia have adopted advanced forecasting and warning systems (Brunner & Slater, 2022; Wasko, Guo, et al., 2023), whereas many developing countries still lack access to high-resolution data, technical infrastructure, and long-term monitoring networks. These gaps persist largely because data acquisition is costly, satellite datasets often require post-processing expertise, and hydrological instrumentation networks deteriorate without sustained government investment. As a result, unequal adaptive capacity remains a systemic challenge (Datta et al., 2023; Gangani et al., 2023).

Second, the fragmented nature of research approaches persists because academic, technological, and planning communities often operate in silos. Hydrological–hydraulic modeling, AI/IoT research, and urban planning studies are frequently conducted independently, each with different methodological assumptions, data requirements, and disciplinary incentives (Chitwatkulsiri & Miyamoto, 2023; Zimmermann et al., 2023). Collaboration is further hindered by institutional barriers, incompatible software systems, and the absence of unified standards for integrating simulation outputs into planning or governance workflows. As a result, high-tech experiments remain weakly connected to on-the-ground decision-making.

Third, uncertainty in forecasting and modeling remains inadequately addressed. Although hybrid 1D–2D models and AI techniques have improved predictive accuracy, many studies do not systematically quantify uncertainties associated with climate scenarios, land-use change, drainage infrastructure characteristics, and human behavior (Schmitt & Minderhoud, 2023). These oversights persist because uncertainty analysis demands substantial computational resources as well as systematic comparison across multiple models and scenarios. Many research teams do not have access to the advanced infrastructure, interdisciplinary expertise, or long-term datasets required to carry out these tasks rigorously. Government agencies, particularly in developing contexts, often face additional constraints related to limited staffing, budget pressures, and fragmented mandates, which make comprehensive uncertainty evaluation difficult to institutionalize. As a result, model robustness tends to be overstated, and the practical reliability of forecasting tools becomes constrained, reducing trust and limiting their applicability in real decision-making settings.

Fourth, issues of social equity and community capacity continue to hinder flood resilience. Marginalized groups often face the greatest exposure to flooding, yet they are the least represented in planning and decision-making processes. This gap persists because risk communication is uneven, local institutions may lack participatory mechanisms, and data on vulnerable populations remain scarce or politically sensitive. Integrating climate justice, public participation, and co-production of knowledge into flood governance remains an ongoing challenge (Flores et al., 2023; Kovaleva et al., 2023).

Finally, limited cross-border cooperation and data-sharing mechanisms restrict progress on transboundary flood risks. Although initiatives such as the EU Floods Directive and Sponge City programs have demonstrated the value of shared platforms and standardized protocols (Griffiths et al., 2020; Jones et al., 2023), many regions struggle with political sensitivities, inconsistent data formats, and intellectual property concerns that hinder the free exchange of hydrometeorological information. These barriers make it difficult to develop basin-wide flood models or coordinated early-warning systems.

Taken together, these challenges highlight that gaps persist not only because of technical limitations, but also due to structural inequalities, institutional fragmentation, and insufficient coordination between science, policy, and community systems. Understanding these underlying causes is essential for developing more effective and equitable flood risk management strategies.

5.2. Identified Gaps in Current Flood Research

Despite the substantial growth of urban flood research in recent years, several persistent gaps continue to limit the effectiveness of scientific and policy responses.

First, the lack of high-resolution data continues to be a major challenge in many developing countries. Studies in South Asia and Southeast Asia show that hydrometeorological data, digital elevation models (DEMs), and satellite imagery are often of low resolution, falling short of the requirements for detailed urban flood modeling and leading to inaccurate forecasts (Datta et al., 2023; Sharma et al., 2023). Shen et al. (2023) also emphasized that the absence of long-term, high-quality observational data undermines risk assessment capacity in coastal areas exposed simultaneously to sea-level rise and extreme rainfall (Shen et al., 2023).

Second, the practical application of numerical models remains limited. Although many hydrological–hydraulic and hybrid models have been developed, most studies remain at the experimental or academic level, while implementation in early warning systems and urban management is still very restricted (Chitwatkulsiri & Miyamoto, 2023). Researchers such as Schmitt and Minderhoud (2023) pointed out that current models often fail to account for uncertainty, are difficult to integrate with real management systems, and demand computational resources and data that many localities cannot provide (Schmitt & Minderhoud, 2023; Seeger et al., 2023).

Third, integration between urban planning, simulation technologies, and local community participation is still insufficient. Wang et al. (2023) analyzed that studies on drainage infrastructure and stormwater management are often disconnected from overall urban planning and poorly aligned with community needs (Wang et al., 2023). Flores et al. (2023) showed that in Houston, USA, spatial planning disparities and unequal access to information have exacerbated flood risk inequities (Flores et al., 2023). Similarly, Zimmermann et al. (2023) noted that in Mumbai, despite extensive technical studies, community involvement in risk management remains limited, creating a persistent gap between science and policy (Zimmermann et al., 2023).

In summary, current research gaps can be consolidated into three main points: (i) insufficient high-resolution data, especially in developing countries; (ii) limited transfer of numerical models from research to practical applications; and (iii) lack of comprehensive integration between technical science, urban planning, and community participation. These three gaps provide a concrete agenda that subsequent sections translate into directions for methodological innovation, planning integration, and governance reform. Table 3 summarizes the three major research gaps, highlights the structural causes behind their persistence, and outlines potential remedies that inform the future research directions discussed in the next section.

Table 3. Summary of key research gaps, underlying causes, and suggested remedies in urban flood studies

Identified Gap	Underlying Causes (Why the Gap Persists)	Suggested Remedies (What the Literature Proposes)
1. Insufficient high-resolution data	- High cost of hydrometeorological instrumentation and satellite data processing- Limited long-term monitoring networks in developing countries- Weak institutional capacity for data management and maintenance- Fragmented data ownership across agencies	- Expand open-access data initiatives and remote-sensing programs- Invest in national hydrological monitoring networks- Strengthen technical capacity for data processing and quality control- Establish unified data-sharing platforms

2. Limited practical application of numerical models	- Most models developed in academic settings without operational alignment- Lack of uncertainty quantification reduces trust in model outputs- High computational and data requirements exceed local capabilities- Weak integration between modeling tools and decision-support systems	- Co-develop models with government agencies to ensure operational relevance- Standardize uncertainty reporting, sensitivity analysis, and model validation- Promote lightweight, open-source, and cloud-based modeling tools- Integrate model outputs into early-warning and urban management platforms
3. Poor integration between science, urban planning, and community participation	- Planning and technical sectors operate in disciplinary silos- Limited participatory mechanisms and unequal access to risk information- Lack of incentives or institutional mandates for cross-sector collaboration- Underrepresentation of vulnerable communities in decision-making	- Adopt transdisciplinary planning approaches linking hydrology, planning, and governance- Strengthen participatory risk assessment and community-led data collection- Improve risk communication and public access to flooding information- Embed socio-economic and equity considerations into planning and resilience frameworks

5.3. Proposed Directions for Future Research

In the context of increasingly complex urban flooding driven by the combined effects of climate change, extreme rainfall, and rapid urbanization, future research directions should focus on developing comprehensive solutions grounded in science, technology, and governance (see the Figure 2).

First, priority should be given to the development of flexible, high-performance simulation and forecasting models capable of integrating hydrological–hydraulic models (1D/2D/3D) with satellite data, IoT sensor data, and community-based data. These models should be able to process big data in real time, allow rapid calibration, and utilize open data sources to enhance applicability in data-scarce regions (Henriksen et al., 2022; Shen et al., 2023). In parallel, the application of artificial intelligence (AI), machine learning, Big Data, and the Internet of Things (IoT) in urban flood risk management is a highly promising research avenue. AI can support early detection and forecasting of extreme rainfall, while IoT enables distributed sensor networks to monitor water levels, flow velocity, and urban infrastructure conditions. Big Data provides a foundation for integrating and analyzing heterogeneous data sources (satellite data, GIS maps, social media, traffic cameras) to support fast and accurate decision-making in emergencies (Ariyachandra & Wedawatta, 2023; Riaz et al., 2023). Emerging directions may include developing digital twins of cities for multi-scenario simulation, or exploring blockchain technology to ensure transparency and security in risk data sharing (Ariyachandra & Wedawatta, 2023; Riaz et al., 2023).

To increase their real-world effectiveness, future research must also focus on embedding AI/IoT systems within governance frameworks rather than treating them as stand-alone technical tools. This requires the development of institutional protocols specifying: (i) how model outputs feed into zoning regulations, infrastructure investment decisions, and emergency response plans; (ii) which agencies have authority to validate, interpret, and act upon AI-generated forecasts; and (iii) how responsibilities are coordinated across municipal, regional, and national levels. For example, flood forecasts generated by AI models should be linked to predefined action thresholds that automatically trigger warnings, temporary road closures, or drainage system operations. Similarly, IoT sensor data on real-time water levels can be incorporated into municipal dashboards used by disaster management authorities to allocate resources, mobilize evacuation teams, or prioritize maintenance of critical infrastructure. Integrating these technologies into governance frameworks also requires attention to data accountability, ethical standards, and transparency, ensuring that predictive models inform inclusive and equitable decision-making processes.

Another important focus is embedding technology into climate-adaptive urban planning and design. Future studies should explore ways to integrate flood models into green–gray infrastructure planning, such as sustainable urban drainage systems (SUDS), green roofs, retention ponds, and Nature-based Solutions (NbS)

(Rezvani et al., 2023; Sharifi & Khavarian-Garmsir, 2022). This approach not only reduces flood risks but also delivers co-benefits for the environment, ecology, and public health.

Finally, strengthening international cooperation and cross-border data sharing is a critical direction. Many cities and river basins span multiple countries, requiring regional mechanisms for sharing hydrometeorological data, establishing global open data repositories, and developing common platforms for early warning and modeling. International organizations such as UNDRR, WMO, and transcontinental research networks can play coordinating roles, enhancing research capacity and practical application in developing countries (Ajibade et al., 2023; G. Yang et al., 2023).

In short, future research on urban flooding needs to integrate three essential dimensions: advanced technology, climate-adaptive planning, and global cooperation, in order to build smart urban systems that are resilient, flexible, and equitable in the face of escalating climate challenges.

6. Conclusion

Research on urban flooding has expanded significantly in both volume and scope, reflecting global concern over the mounting challenges of climate change, extreme rainfall, and rapid urbanization. The main contribution of this review lies in synthesizing and categorizing more than two decades of research, identifying developmental trends, achievements, limitations, and practical implications, while outlining strategic directions for future studies. These findings not only help position current scientific knowledge on urban flooding but also serve as a bridge between research, policy, and practice, contributing to the development of smarter, more sustainable, and more resilient cities in the face of global climate change.

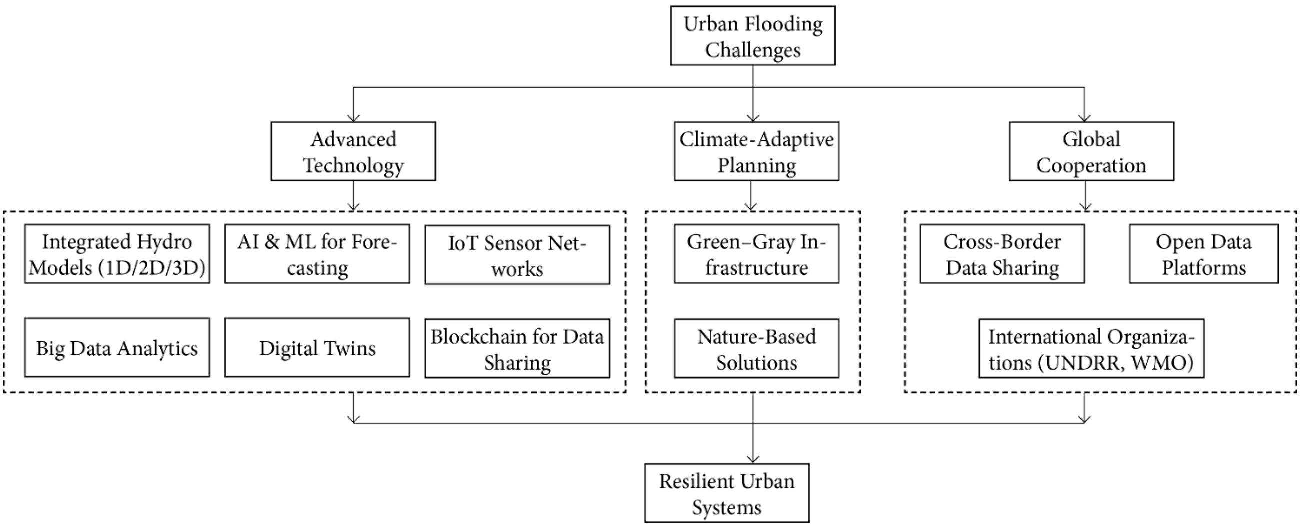

Figure 2. Diagram of strategic directions and technologies for future urban flood research

This review provides a comprehensive overview of the trajectory of urban flood research, clarifying major achievements as well as persistent gaps, such as the shortage of high-resolution data in many developing countries, the limited practical application of numerical models, and the lack of integration between technical science, urban planning, and community participation. Building on these insights, the article outlines strategic directions for future research that prioritize flexible, open-data-based simulation models; the integration of AI/Big Data/IoT into warning and risk-management systems; the embedding of nature-based solutions in climate-adaptive urban design; and stronger international cooperation with cross-border data sharing.

Beyond these directions, several practical implications can also be drawn. In particular, integrated end-to-end systems that link physical models, observational data, and AI/IoT platforms to local decision-making can enhance risk-management effectiveness, while standardized uncertainty reporting and multi-model cross-validation will improve scientific reliability. The incorporation of NbS and SUDS into urban planning should be accompanied by assessments of social–ecological co-benefits, and open data infrastructures need to be supported by robust governance mechanisms to ensure privacy, transferability, and usability.

From a policy perspective, the findings underscore the need for regulatory frameworks that can accommodate rapidly evolving technologies while ensuring accountability, transparency, and equity. Governments must develop clear protocols for how AI-based forecasts trigger actionable responses, allocate resources for maintaining long-term monitoring networks, and facilitate data interoperability across agencies. Moreover, interdisciplinary cooperation—linking hydrologists, planners, computer scientists, social scientists, and policymakers—will be essential to overcome persistent silos and translate scientific advances into deployable, community-centred solutions. Such collaboration can help integrate technical innovations with land-use planning, social vulnerability assessments, and participatory governance, ultimately strengthening climate resilience across diverse urban contexts.

However, this study also has limitations. Restricting the selection to English-language publications may lead to language bias, while the review period ending in 2023 inevitably risks missing more recent studies. In addition, no meta-analysis was conducted due to substantial differences in metrics across technical, social, and policy-oriented research, which limits the scope for quantitative synthesis.

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